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EXPLORATORY WORK WITH PRE-MIXING INJECTORS FOR NITRIC ACID - KEROSENE ROCKET MOTORS

by

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4 Exploratory Work with Pre-mixing Injectors for Nitric Acid - Kerosene Rocket Motors

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SUMMARY

This note describes exploratory work carried out to assess the practicability and performance of pre-mixing injectors employed in nitric acid - kerosene rocket motors. With pre-mixing injectors the propellants are mixed before injection into the combustion space, the advantages to be expected being those accruing from improved mixing and more uniform distribution of propellants in the combustion space, i.e. improved efficiencies at lower chamber characteristic lengths and consequently benefits in weight and heat transfer characteristics.

The results obtained, although largely empirical, indicated that the use of pre-mixing injectors of the centrifugal swirl type was practicable and that better combustion was realizable than with conventional impinging jet type injectors. Ignition and shut down, however, presented difficulties which it was clear could only be overcome by more careful control of propellant entry and cut off than was possible with the propellant control valve then available. It was, therefore, decided to postpone the completion of the programme in favour of work on more conventional types of injectors, pending the development of more precise methods of propellant control.

1. Nitric acid
2. Kerosene
3. Injectors

I. Frauenberger, H.

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LIST OF CONTENTS

APPENDIX

TABLE

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Contd.)

1 Introduction

In a liquid bi-propellant rocket propulsion system, the assembly that may be regarded as the motor proper comprises four basic components, the propellant control valves, the injector or burner, the combustion chamber, and the nozzle or venturi. The function of the injector is to introduce the liquids into the combustion space in a form favourable for combustion. The combustion chamber provides the space in which the potential chemical energy of the propellants is transformed into heat energy, chemical reaction producing gases at high temperature and pressure from which useful energy is extracted during the expansion of the gases through the nozzle.

In seeking to increase the efficiency of the motor in terms of motor weight per unit thrust, a most substantial weight reduction can be achieved by decreasing the size of the combustion chamber. In addition, the cooling problem is eased by decreasing the size of the chamber and also the internal surface exposed to the hot gases. A constant aim of the development is thus to produce motors with the minimum chamber volume necessary to enable the propellants to react without undue loss of combustion efficiency.

In considering how to achieve this end, some understanding of the processes occurring in the combustion space is obviously needed. Unfortunately, at the present stage of research, precise knowledge is lacking, and the approach must perforce be largely empirical. The processes may, however, be separated into the physical ones of mixing atomizing and vaporizing the propellants followed by chemical reaction. Since there is a continuous flow through the combustion space, the volume required is related to the time needed to complete the above processes. To some extent the several processes probably proceed concurrently, so that the minimum time (or volume) for completion is almost certainly not obtained by direct addition. It has, indeed, been suggested that the minimum volume may be largely related to the time needed for the slowest of the individual processes to go substantially to completion. It seems reasonable, however, to suppose that the complete sequence is affected by the method of injection of the propellants. The effect might be expected to be most marked if the physical processes are the limiting ones, although uniformity of injection must also affect the overall rates of the chemical reactions.

Assuming that the combustion pressure (increase of which decreases the chamber volume needed) is fixed by other considerations, improvement of injection is the obvious method of tackling the problem of reducing chamber size.

With conventional types of injectors, such as the widely used impinging jet, the propellants are injected separately, and mixing and atomization are arranged to occur within the combustion space. A fundamental defect is that the requirements of mixing and atomization tend to be incompatible. In addition, during the critical ignition period it may well be that the spray is neither well mixed nor atomized, since time is required for the build up of adequate injection pressures. That general mixing and distribution during firing may be poor is shewn by Fig. 1a and 1b, which present analyses of the exhaust gases across the exit of a rocket motor nozzle using two different injectors[1].

With pre-mixing injectors the propellants are intimately mixed in the correct ratio prior to injection into the combustion space. The design of the injectors can then be concentrated on achieving good atomization and distribution, without the handicap of arranging for mixing to occur after injection. The advantages to be expected are

those arising from good distribution and intimate mixing[2] combined with good atomization, that is, more rapid completion of combustion. Since pre-mixing injectors deliver a mixture of propellants, it is to be expected that ignition may be easier even at low injection pressures. One disadvantage is the risk of explosion of the quantity of mixed propellant present within the injector itself.

Some tests were carried out in Germany during World War II employing pre-mixing injectors in a motor of about 2000 lb thrust. The propellants were Salbei* and Tonka**, a hypergolic combination. Work was discontinued because of the high incidence of explosions, particularly at initiation. The results of Kroekel's[3] mixing nozzle investigation, carried out at Volkenrode, were also not encouraging. Nitric acid and a hypergolic fuel were injected through a double swirl injector (see Fig.2). Ignition was not positive and occasionally explosions occurred. No firings were carried out in combustion chambers. Merrington[4] gives some information relating to tests of pre-mixing injectors for the liquid oxygen-alcohol combination carried out by the Bell Aircraft Corporation. The individual propellants were admitted tangentially into the swirl chamber of a normal swirl type injector. Again explosions were liable to occur after a few seconds running.

In all the above cases, however, investigation was dropped without any persistent attempt having been made to overcome the problems encountered.

2 Present investigation

When the work described below was initiated, information about the fundamental requirements of the injection of nitric acid - kerosene mixtures was completely lacking, as also was any knowledge of ignition delays, detonation risks and rates of flame propagation under different pressure and temperature conditions. No prior assessment of the feasibility of employing pre-mixing injectors with this propellant combination could, therefore, be made.

Preliminary tests reported by Diederichsen, Walder and Treutler[5] showed that the centrifugal swirl type injector would produce a finely atomized spray of emulsified water - kerosene, each droplet containing the constituents in the proportion in which they were fed to the injector. Mixing could be arranged to occur either prior to entry into the injector proper, or actually within the swirl chamber.

For the first tests, therefore, it was decided to use single centrifugal swirl type injectors, and a convenient size having a throughput of combined propellants of 1 lb/sec was selected. Qualitative assessments of combustion were made initially by visual examination of the flame during open burning, followed by combustion chamber firings with measurements of pressure and thrust. Following fair success with this small scale work, some firings were carried out at a larger throughput (10 lb/sec) by increasing the number of swirl injectors set in the injector headplate, the preliminary trials having indicated that this was preferable to scaling up a single injector.

As will be seen, however, the investigation was not carried beyond the exploratory stages. The work described was completed in mid 1949.

3 Test stand and equipment

The work herein described was practically the first carried out at R.P.D. with nitric acid as the oxidant, so that the development of test

* 96% nitric acid with N_2O_4 and water

** mixture of organic chemicals

stand facilities, instrumentation and procedure proceeded concurrently with this investigation[6]. In consequence, setbacks due to lack of experience and particularly to mechanical and material failures were numerous. These were largely instrumental in leading to the postponement of the investigation.

3.1 Description of test stand and equipment

The layout of the test rig is shown diagrammatically in Fig.3. The nitric acid tank was constructed as described by Wheeler[7], and consisted of a mild steel outer tube with a pure aluminium liner. The kerosene tank was constructed from a high pressure gas cylinder. The propellants were expelled by nitrogen pressure, both tanks being pressurized from a common feed line and vented through a common vent. The quantities in the tanks could be measured before and after a firing from sight level glasses attached to the tanks.

The entry of the propellants to the injector was controlled by propellant control valves located immediately behind the injector head. Provision was made for blowing nitrogen through the injector at the end of a firing in order to get rid of any propellants remaining in the injector passages.

Pressures were measured by Bourdon gauges and in some cases also recorded on a mechanical Maihak strip recorder. An electronic method became available at a late stage and proved invaluable for recording transients, such as pressure peaks at ignition and vibrations during firing.

In early tests, the injector head was mounted on a tripod stand (see Fig.4), and the axis of the combustion chamber when fitted was inclined downwards at an angle of 45°. This arrangement was made to avoid the accumulation of propellants in the chamber, and thus to reduce the power of any explosion that might occur. Later the parallelogram type of rig now generally used (see Fig.5a and 5b) was adopted. The motor thrust was measured by means of a hydraulic unit incorporating a stainless steel bellows and coupled to a Bourdon gauge.

18/8 stainless steel and pure aluminium were used exclusively for all parts of the equipment in contact with nitric acid.

3.2 Propellant control valves

In the earlier tests, pneumatically operated valves of German design[8] and manufacture (see Fig.6) were employed as main propellant control valves in both the nitric acid and kerosene feed pipes. These valves were made in an aluminium alloy and were operated by nitrogen under pressure controlled by a solenoid valve. Since these valves were designed for "one-shot" operation, it was not surprising that, when used continuously on the test-rig, they were liable to leak and also tended to seize. Reasonably satisfactory functioning was attained after carrying out the following modifications:

(a) The material of the valve stem was changed to 18/8 stainless steel.

(b) The sliding surfaces were chromium plated to a depth of 0.002 inch approximately.

(c) The valve seating material was changed to moulded polythene. This material had a tendency to harden in use and required renewing after about two months.

Later the type of valve shown in Fig.7, and made of stainless steel, was introduced[6]. These valves were also operated pneumatically initially. As a result of experience, however, they were subsequently operated by water pressurized by nitrogen. Reliable and reproducible control of the opening and closing characteristics could be achieved by metering the water passages. After initial troubles, which were largely overcome by attention to sliding clearances and the chromium plating of sliding surfaces (chromium plating was essential also where the grades of stainless steel in contact were dissimilar), these valves proved satisfactory.

4 Experimental procedure

4.1 Choice of mixture ratio

The thermodynamic assessment of the nitric acid - kerosene reaction indicated that the maximum performance should be obtained with a mixture ratio of 5 parts by weight of 98% white fuming nitric acid to 1 part of aviation turbine fuel (Specification R.D.2482). At this ratio, the reaction temperature is also near the maximum, but in the absence of any detailed knowledge of the heat transfer problem at that time, there seemed to be no reason for choosing a ratio with lower reaction temperature at the expense of performance. The ratio throughout the present investigation was, therefore, nominally 5 to 1. Propellant throughputs were adjusted by fitting suitable chokes in the feed lines as indicated by water flow tests carried out with the injector head on the test rig before the actual firings.

4.2 Sequence of injector tests

The test sequence adopted for assessing the qualities of an injector was as follows:

(a) Open firing

During this test the flame was observed visually and photographically. Ignition was studied and the subsequent burning was judged by the position of the flame relative to the face of the injector plate, as well as by the shape, colour, general appearance, and stability of the flame.

(b) Open tube firing

The injector head was fitted into a tube the diameter and length of which were generally the same as those of the chamber to be fitted subsequently. Combustion was again observed visually. An examination of the tempering on the surface of the tube after firing often gave a useful indication of the position of the flame front.

(c) Combustion chamber firing

A restrictor plate with an orifice was fitted into the end of the tube. The size of the orifice was decreased from firing to firing, so that the internal chamber pressure was progressively increased. Chamber pressures were measured and, in conjunction with the propellant throughput rates, were used to calculate overall performance figures. Various designs of chamber and restriction, uncooled and water cooled, with plain chokes and fully contoured nozzles, were used in the course of the investigation.

4.3 Ignition

Two methods were investigated:-

(a) Third fluid ignition

A small quantity of a fluid that ignites spontaneously with nitric acid was introduced into the injector ahead of the main fuel. This self igniting fuel was contained in the main fuel line, but in a separate container as shown in Fig.3. The fluid used was W.A.F.1, a mixture of 70% furfuryl alcohol and 30% aniline by volume, the ignition delay of which with nitric acid at normal temperatures is approximately ten milliseconds.

(b) Solid ignition

An igniter, fired electrically, was fixed to the injector head in such a position that the propellant spray was exposed to the igniter flame. Two types of igniter were tried:

(1) Plastic igniter. This was similar to that used in the R.T.V.1 motor. These igniters were filled with plastic composition R.D.2633 and had the following characteristics -

charge weight	70g
burning time	6 - 7 sec.
heat output	1000 cal/g/sec

(2) Pyrotechnic igniter. The filling was a composition containing aluminium and barium nitrate, known as S.R.135; this provided a much higher rate of heat output at a higher temperature than the plastic igniter. The characteristics are as follows -

charge weight	70 g
burning time	6 - 7 sec.
heat output	1500 cal/g/sec

5 Summary of experimental observations

5.1 Small scale tests at a flow rate of 1-2 lb/sec

Tests were carried out on six different designs of injector head, the injectors in all cases being of the centrifugal swirl type. The details of the results are given in the appendix as follows:

Injector	Head	No.1	Figure	8	Appendix I	para.1
"	"	2	"	9	"	" 2
"	"	3	"	10	"	" 3
"	"	4	"	11	"	" 4
"	"	5	"	12	"	" 5
"	"	6	"	13	"	" 6

The mixing of the propellants took place in the passages prior to their entry into the swirl chambers of the injectors in heads Nos.1, 2 and 4, and inside the actual swirl chambers in No.3, 5 and 6.

In all, over 100 firings were carried out, including some 60 at low combustion chamber pressures and about 15 at chamber pressures between 200 and 325 lb/sq in. A rather large number of firings (40 to 50%) was not completely satisfactory, the higher percentage of failures being traceable to faulty valves, defective igniters, pipe-line fractures and other extraneous mechanical faults. Few reliable quantitative results were obtained, but many useful deductions were made even from firings classed as unsuccessful.

5.11 Ignition

With injector head No.1, and a total propellant flow rate of 1 lb/sec at an injection pressure of 150 lb/sq in, it was found that three of the plastic igniters were sufficient for ignition in the open. In a chamber, however, hard starts (pronounced pressure peaks) were observed; it was deduced that the igniters did not supply sufficient heat for ignition without appreciable delay and that the hard starts were caused by the accummulation of the propellants in the combustion chamber during the delay period.

For injector head No.2 third fluid ignition was adopted and a separate igniter with an impinging jet and target plate was provided. Through this were fed nitric acid and W.A.F.1, the latter being followed after about 2 seconds by kerosene; the igniter-injector was kept running throughout the firing period of some 8 to 10 seconds. The flow rate was 0.4 lb/sec for the igniter-injector and 0.6 lb/sec for the four pre-mixing swirl injectors, at feed pressures of 150 lb/sq in. Combustion chamber ignition was still hard, however, and the assembly was finally destroyed by the premature entry of W.A.F.1 in the chamber owing to an air lock in the acid line.

The igniter and main injectors were combined in injector No.3, a spray of W.A.F.1 being injected into the centre of the conical spray of mixed acid and kerosene. Flow rates were 1 lb/sec of combined propellants with an additional 0.25 lb/sec of W.A.F.1, the feed pressures being the same as before; W.A.F.1 and acid were admitted first, followed after 2 to 3 seconds by kerosene after which the W.A.F.1 could be switched off. In later tests with this injector, all three fluids were admitted simultaneously and the W.A.F.1 was shut off after ignition. Ignition was smooth and reliable, both in the open and in a combustion chamber.

Injector head No.4, was similar to No.2 and incorporated a separate igniter-injector with an impinging jet and target plate, together with four mixing injectors. The improved propellant control valves became available at this stage and the pipe lines were altered so that both the igniter and the main injector could function independently. Ignition was satisfactory as long as the total flow through the four mixing injectors was not more than about three times the flow through the igniter-injector. A similar arrangement was employed with success for ignition in injector head No.5.

Injector head No.6 employed an S.R.135 igniter. Ignition at full flow, up to 2 lb/sec at 150 lb/sq in injection pressure, was reasonably smooth.

The requirements for safe ignition may be summarized as follows:

(1) Heat must be supplied at an adequate rate. This requirement was best met by the use of S.R.135 type igniters. For larger flow rates than those obtained with these injector heads, the use of separate W.A.F.1 injectors would raise difficulties owing to the large proportion of the total throughput needed for ignition. Ignition by feeding the W.A.F.1 also through the mixing injectors was not attempted.

(2) The relative timing of entries of the propellant liquids must be correct. This could not be achieved with perfect reliability with the propellant control valves available. However, although hard starts due to mistiming were encountered frequently, only one caused the destruction of the motor.

5.12 Combustion efficiency

With all these injector heads, combustion once established was good, i.e. the flame front was stable and close to the injector; the exhaust was

clear with a short flame and was free from fumes. With those injector heads incorporating a separate igniter-injector, it was possible to switch off the mixing injectors and re-ignite without trouble. Owing to the lack of reliable cooled combustion chambers, it was not possible to do long runs in order to obtain accurate figures for specific impulse. Some figures for injector head No.4 and 5 are given in the Table, and indicate an efficiency of the order of 86% of theoretical, no allowance having been made for nozzle and associated losses, which would be of the order of 7%.

5.13 Risks and precautions

It was found that minor explosions were liable to occur after shut-off with injector head No.1, presumably on account of the 'cook-off' of the mixed propellants left in the injector passages. This danger was obviated by blowing nitrogen through the system after the end of the firing. This was not necessary with the other injector heads. However, injector head No.4 was destroyed during a firing owing to insufficient cooling of the head; the explosion occurred inside the mixing passages.

There was also a tendency for a minor explosion to occur at shut-off. This was attributed to the flame front entering the swirl injectors as the injection velocity decreased, and the likelihood was reduced by the more rapid closing of the main propellant control valves.

5.2 Tests at about 10 lb/sec flow rate

If a centrifugal swirl type injector is scaled up in dimensions in order to handle a bigger throughput at constant injection pressure, the atomization becomes worse. For larger flow rates, therefore, the number of swirl injectors fitted in the injector head was increased.

Three designs of injector head were tried, employing ignition by S.R.135 igniters throughout:

Injector	head	No.7	(Fig.14)
"	"	8 & 8(a)	(Fig.15)
"	"	9	(Fig.16)

Injector head No.7 incorporated 20 swirl injectors positioned on two pitch circle diameters round a recessed igniter housing for the single S.R.135 igniter employed. Mixing took place within the passages enclosing this housing. This injector head was destroyed on ignition in a chamber. The explosion occurred inside the injector and was thought at first to have been due to hot slag from the igniter entering one of the injectors. Further investigation, however, led to the conclusion that it could have been caused by the overheating of the mixed propellants in the passages round the igniter pocket.

Injector heads No.8 and 8(a) were similar, except that No.8(a) had a circle of 10 swirl injectors in addition to the 20 of No.8, the throughput being correspondingly increased. The igniter was not recessed as in No.7, and mixing occurred in a space behind the face of the injector head. With these two injector heads a total of 60 to 70 firings at low chamber pressures (up to 260 lb/sq in) were completed. Injector head No.8 was finally destroyed owing to the burning away of the uncooled periphery. Injector head No.8(a), which was designed with better cooling at the periphery, was destroyed after nearly 50 firings by a hard start due to an accidental accumulation of kerosene. In general, ignition was not consistent, which was deduced to be due either to insufficient heat output from the igniter, or to inconsistent arrival times of the propellants. The mixture ratio also varied considerably.

Injector head No.9 incorporated 30 swirl injectors arranged on three pitch circle diameters. Mixing took place in the swirl chambers only, the propellant passages being arranged to give maximum cooling over the face of the injector head. This arrangement reduced the likelihood of the mixed propellants exploding and also decreased the quantity of propellant available to explode within the injector head. Ignition was inconsistent, and continued to be so even when as many as four S.R.135 igniters were used together. Non-reproducible opening of the propellant valves was deduced to be the reason. A number of runs (14) were made at low pressures with throughputs of the order 8 lb/sec. After ignition, combustion usually appeared to be good, but the investigation was dropped before any considerable work had been done with this injector head.

6 Conclusions

The value of the investigation lay chiefly in the experience gained in tackling the problems of test stand operation, the design of equipment in suitable materials, instrumentation and the handling of nitric acid - kerosene propellant systems.

The observations made of the performance of pre-mixing injectors for comparison with other types of injector were almost entirely qualitative. It can be stated, however, that with pre-mixing injectors of the centrifugal swirl type, combustion appeared to be distinctly better than with conventional impinging jet injectors, the flame was stable, well defined and clean and started close to the injector. Such quantitative figures as were obtained, indicated that specific impulses of at least 95% of the theoretical value might be expected.

The presence within the injector of a quantity of mixed and, therefore, explosive liquid presented a risk of explosion if this liquid was overheated or if the flame for some reason travelled back inside the injector. The risk of over heating could be eliminated by careful attention to the cooling of the injector head in design. The flame was most likely to travel backwards at ignition before the injection velocity was built up and the flame front stabilized, or at shut down, and this risk should be overcome by ensuring a reliable control of the propellant entries and cut off. In any case, the design should be such that the quantity of mixed propellants present inside the injector passages is kept to a minimum by arranging that mixing occurs only inside the swirl chamber proper.

The problem of the control and synchronization of the times and rates of entry of the propellants relative to each other and relative to the period of burning of the igniter could not be satisfactorily solved with the propellant control valves available at that time; the difficulties could, however, be overcome by using a type of valve in which the movements of the pintles on the acid and kerosene sides are positively coupled and controlled to give a matching build-up of relative throughputs during the initial stages and then during the run. Another method of eliminating the dangerous initial period when the injector is not delivering the liquids at full pressure and is, therefore, not atomizing and distributing them effectively, might be to insert soluble chokes in the injector exit orifices, so that the quantities injected at low pressure could be minimized.

A coupled valve of this type was being designed during the later stages of this investigation, but it was not completed in time to be employed.

In the absence of such devices and in view of the continued destruction of equipment by the consequent hard starts and other mishaps, it was decided to postpone the investigation in favour of the development

of motors employing less sensitive means of injection. When some of the other problems of operating nitric acid - kerosene motors have been cleared up, e.g. when reliable cooled combustion chambers have been developed, so that long firings can be successfully carried out to yield accurate specific impulse figures, it will be worthwhile continuing the investigation of pre-mixing injectors.

Acknowledgement

Thanks are due to Dr. R.P. Hagerty for his assistance in the preparation of this Technical Note.

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APPENDIX

Test Results - Small Scale Work

1 Injector head, No.1 (Fig.8)

This was a centrifugal swirl injector based on the Walter 109/509 design but modified for pre-mixing. The central swirl chamber (oxidant) was converted into a mixing chamber by drilling tangential holes connecting to the outer (fuel) annulus. The injector was adjusted to pass a total flow rate of combined oxidant and fuel of 1 lb/sec at an injection pressure of 150 lb/sq in.

1.1 Operation

The plastic igniter was initiated three seconds before admitting the propellants. The duration of each firing was about 10 seconds. The propellants remained in the supply lines and injector after firing.

1.2 Observations

It was found that three igniters were necessary for reliable ignition in the open. Open firings were satisfactory; the flame front stabilized roughly one inch from the injector. Combustion in an open tube was also satisfactory. In a chamber fitted with a restriction designed to give 200 lb/sq in chamber pressure, ignition tended to be harsh, but once initiated combustion was good and fumeless. After an explosion had occurred after shutting down, a happening ascribed to "cook-off" of residual mixed propellants, it was decided to blow through with nitrogen after each firing.

1.3 Conclusions

It appeared that three plastic igniters were incapable of supplying heat to the propellants in the combustion chamber at a sufficient rate at full flow conditions in the chamber to avoid hard ignition owing to the accumulation of propellants.

2 Injector head No.2 (Fig.9)

In this design, the propellants were mixed in an annular space prior to entering the injectors proper, of which there were four of the swirl type, equally spaced on a pitch circle of 2/3 chamber diameter. The axes of the injectors intersected on the chamber axis about $2\frac{1}{2}$ inches from the face of the injector plate. A separate impinging jet/target plate injector for nitric acid and W.A.F.1 was provided for ignition. The total flow rate was 1 lb/sec at an injection pressure of 150 lb/sq in, and of this 0.4 lb/sec passed through the igniter-injector.

2.1 Operation

The igniter-injector was operated for 3 to 4 seconds (the take-over from W.A.F.1 to kerosene occurred after about 2 seconds), and the pre-mixing injectors were then switched on in addition.

2.2 Observations

Open firings were satisfactory, and it was possible to switch the main injectors on and off whilst the igniter-injector continued burning. Several firings of up to thirteen seconds duration were carried out in a water-cooled chamber with an uncooled copper nozzle at combustion pressures of 135 to 150 lb/sq in. Apart from harsh ignition, these

firings were satisfactory. The equipment was finally destroyed when, owing to an air lock in the nitric acid line, W.A.F.1 entered prematurely.

2.3 Conclusions

Owing to the destruction of the injector it was not possible to complete the programme to determine the minimum igniter flow required for a given total propellant flow rate to avoid a harsh start. In view of the harsh ignitions observed, it would appear that a higher percentage of igniter fuel than was used is required. The presence of the mixed propellants in the annulus did not give rise to any explosion or "cook-off" in this design, suggesting that the mixture was not so sensitive as had previously been suspected.

3 Injector head No.3 (Fig.10)

This injector incorporated the igniter system in the main injector, W.A.F.1 being introduced so that it impinged on the hollow cone of mixed propellants. The combined flow rate was 1 lb/sec with an additional $\frac{1}{4}$ lb/sec of W.A.F.1 initially, at an injection pressure of 150 lb/sq in.

3.1 Operation

Nitric acid and W.A.F.1 (the latter through its own passage) were admitted for ignition, and then kerosene, after which the W.A.F.1 was stopped. In later tests, all three were admitted simultaneously and the W.A.F.1 was switched off after ignition.

3.2 Observations

Ignition and combustion were good, both in the open and at combustion pressures of about 200 lb/sq in. While nitric acid, kerosene and W.A.F.1 were all being admitted, the flame was bright and streaky, showing obvious signs of fuel richness. No "cook-off" occurred after shut-down after firings of maximum duration (about twelve seconds).

3.3 Conclusions

Reliable ignition was obtained with a ratio of W.A.F.1 to main propellant flow rate of 1 to 4.

4 Injector head No.4 (Fig.11)

This was similar to injector head No.2, and incorporated the mixing of the main propellants in an annulus prior to their entry into four swirl type injectors arranged round a central igniter-injector of the impinging jet/target plate type. The injector was, however, flat in order to avoid the possibility of W.A.F.1 from the igniter trickling into one of the swirl injectors, as possibly happened when injector head No.2 was destroyed.

In initial tests, the flow rates were $\frac{1}{2}$ lb/sec for the main injectors and an equal throughput for the igniter, at injection pressures of 150 lb/sq in. Later, the throughput of the main injectors was trebled, bringing the total flow rate up to 2 lb/sec, at the same injection pressure.

4.1 Operation

The fuel pipe line leading to the igniter-injector was primed with a slug of W.A.F.1 which lasted for about 1 second before the change-over, the main propellant flow being admitted 2 to 3 seconds later.

4.2 Observations

Open firings were carried out with the igniter-injector only, initially without the target plate. Ignition with W.A.F.1 occurred at a distance of some 10 inches from the injector, and combustion failed at the changeover to kerosene. With the target disc, ignition was observed immediately adjacent to the disc, and the changeover was detectable only by the slight difference in flame colour. Ignition of the main propellant flow by this target plate igniter was reliable and smooth in a chamber designed to give a pressure of 200 lb/sq in; combustion was good. The equipment was destroyed by an explosion due to the malfunctioning of the propellant control valves which were at that time of the first type used (Fig.6).

The latest stainless steel propellant control valves (Fig.7) were then installed. In addition a three-way cock was added to the fuel line of the ignition system, to separate the W.A.F.1 and kerosene containers and to connect them both individually to the igniter system. In this way it was possible to control both fuels independently; with the earlier methods this was an impossible task. It was thus possible to switch over from self-igniting to non-self-igniting fuel, or to switch off both.

Seven open firings and twelve at a chamber pressure of approximately 200 lb/sq in were carried out satisfactorily with this new arrangement, combustion continuing when the ignition system was switched off.

Next the orifice size of the mixing nozzles was increased in easy stages, to find the maximum flow rate ratio relative to the igniter system. Results proved that when this ratio exceeded 2.8 : 1 ignition invariably became hard and difficult.

Finally, a number of firings of 20 seconds duration at a chamber pressure of 300 lb/sq in and an injection pressure of 420 lb/sq in were carried out in order to obtain efficiency figures (See Table). The cooling of the injector head proved insufficient for long firings and the injector was destroyed after a firing, owing to the overheating of the residual mixed propellant.

4.3 Conclusions

(a) This was the first occasion on which the mixed propellants exploded because of excessive heat due to the badly cooled injector flange which became red hot during firing. The temperature of this mixture was not recorded, but similar explosions are unlikely to occur during a run, as long as fresh cold propellants are flowing into the combustion chamber; explosions might occur, however, even with a well cooled injection system when the motor is shut down as heat soaks in from adjacent hot metal.

(b) The minimum fraction of the total propellant flow rate required by the ignition system for reliable starting was one third; this is rather high and, therefore, this igniter system would hardly be practicable for a large motor.

(c) During these firings, efficiency figures of the order of 95% of the theoretical were recorded (See Table). It was not possible, unfortunately, to obtain really reliable figures for the specific impulse owing to the deficiencies of the recording technique, the short duration of the firings and the low thrust scale. The figures quoted should, therefore, only be used as an indication of the order of magnitude of efficiency.

5 Injector head No.5 (Fig.12)

This injector head consisted of six swirl spray nozzles equally spaced on a pitch circle diameter equivalent to $\frac{2}{3}$ of the chamber diameter, together with a central igniter-injector. In order to reduce the quantity of pre-mixed propellant in the injector head, mixing was arranged to occur inside the swirl nozzles. The complete surface of the injector head plate was cooled by both liquids before mixing, otherwise the system was similar to injector head No.4.

A main propellant flow rate of $\frac{2}{3}$ lb/sec and a similar quantity for the igniter system were arranged. Later, the flow rate of the mixing nozzles was doubled, making a combined flow rate of 2 lb/sec.

The ignition system was similar to that used in injector head No.4 except that the nitric acid supply line was common to both igniter and main injector systems, and, therefore, both systems had to be switched on and off simultaneously.

5.1 Observations

Seventeen firings were completed in the open, in a plain tube and at chamber pressures up to 300 lb/sq in. Ignition and combustion were smooth and steady. The ratio of the flow rate through the main injectors and that to the igniter-injector gradually increased from 1 : 1 to 2 : 1, and when the flow rate through the mixing nozzles was nearly double that through the igniter, a pressure peak became apparent when the propellants were ignited. The average duration of these tests was 10 to 12 seconds.

5.2 Conclusions

(a) The cooling of this injector head proved adequate for the test duration of 12 seconds.

(b) When switching on the igniter system and pre-mixing nozzles together, the propellant flow-rate to the igniter had to be not less than half the main propellant flow rate, otherwise hard starts resulted.

6 Injector head No.6 (Fig.13)

This was similar to injector head No.5, but incorporated four swirl nozzles instead of six, and in place of the third fluid ignition system (W.A.F.1) an S.R.135 pyrotechnic igniter fixed centrally on the injector face was employed. The main propellant flow rate was 1 lb/sec at a pressure drop of 150 lb/sq in.

6.1 Observations

The pre-mixed propellants were injected after the igniter had been burning for 2 to 3 seconds. During open firings and those with a combustion chamber pressure of 150 lb/sq in, the ignition and combustion were very smooth and steady for full flow starting conditions, even after the propellant flow rate had been adjusted from 1 to 2 lb/sec.

6.2 Conclusions

At flow rates up to 2 lb/sec pre-mixing injection had been proved to be practicable. It was, therefore, considered at this stage, that more practical value would be gained from investigating pre-mixing in larger scale injection systems.

TABLE

Test Results with Injector Heads Nos.4 and 5

Injector head number		4	5	5
Number of pre-mixing nozzles		4	6	6
Type of igniter		WAF.1	WAF.1	WAF.1
Duration of firing	(sec)	18.6	10.7	10.0
Diameter of venturi-type nozzle	(in)	0.866	-	-
Diameter of orifice plate	(in)	-	1.403	1.403
Feed pressure	(lb/sq in abs)	418	298	298
Combustion chamber pressure	(lb/sq in abs)	315	174	174
Total propellant flow rate	(lb/sec)	1.25	1.916	1.94
Mixture ratio		5:1	5.4:1	5.58:1
Thrust	(lb)	252	323	319
Measured specific impulse	(sec)	202	169	164.5
Theoretical specific impulse	(sec)	230	207.5	204.5
L*		155	60	60

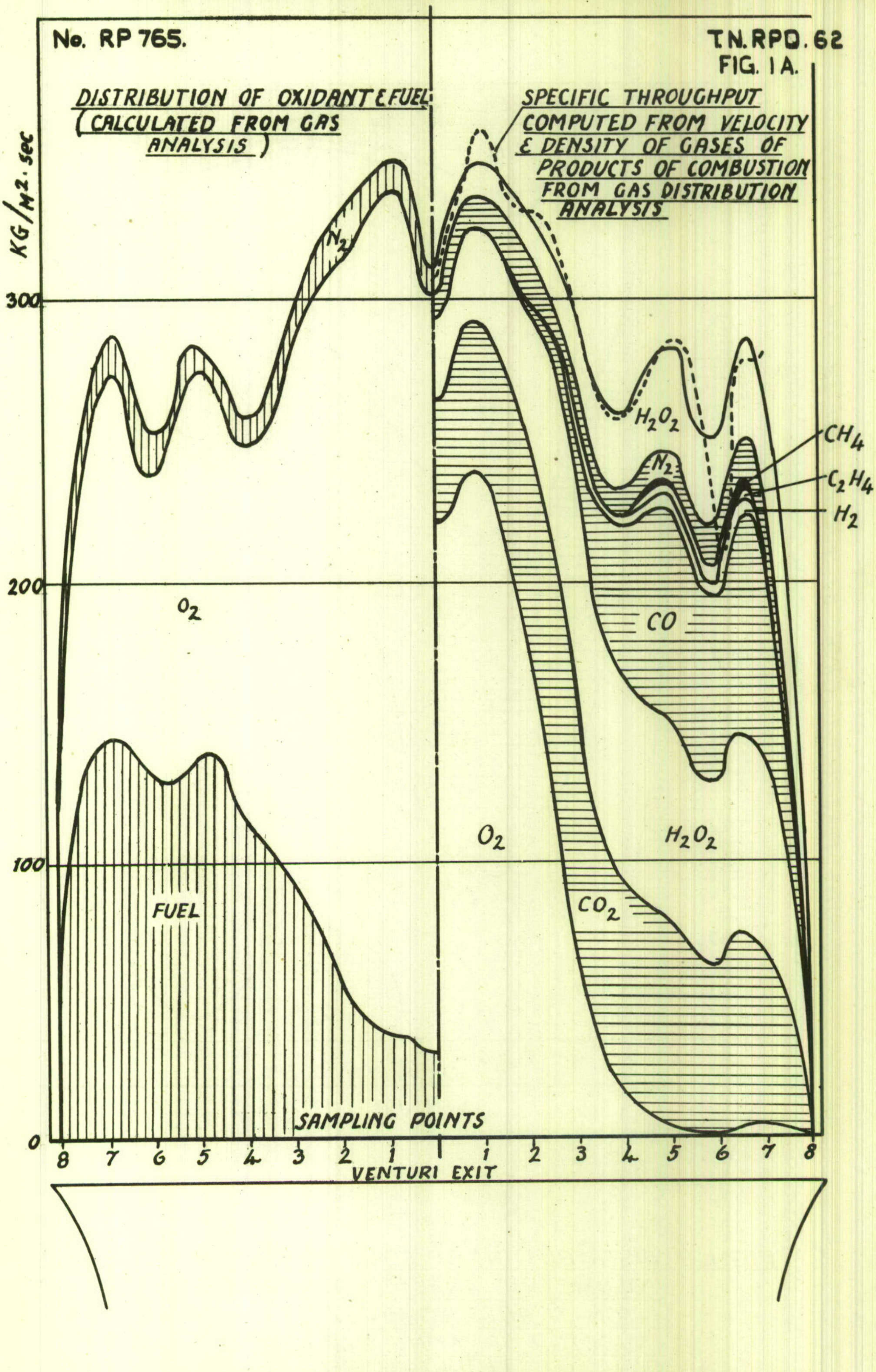


FIG. 1. A DISTRIBUTION OF COMBUSTION PRODUCTS FROM VOLUMETRIC ANALYSIS OF EXHAUST GASES OF 1 TON THRUST COMBUSTION CHAMBER.
INJECTOR: SINGLE V. 2 ROSE
PROPELLANTS: LIQUID OXYGEN, ETHYL ALCOHOL, WATER
SAMPLES TAKEN 10 MM BEHIND VENTURI EXIT

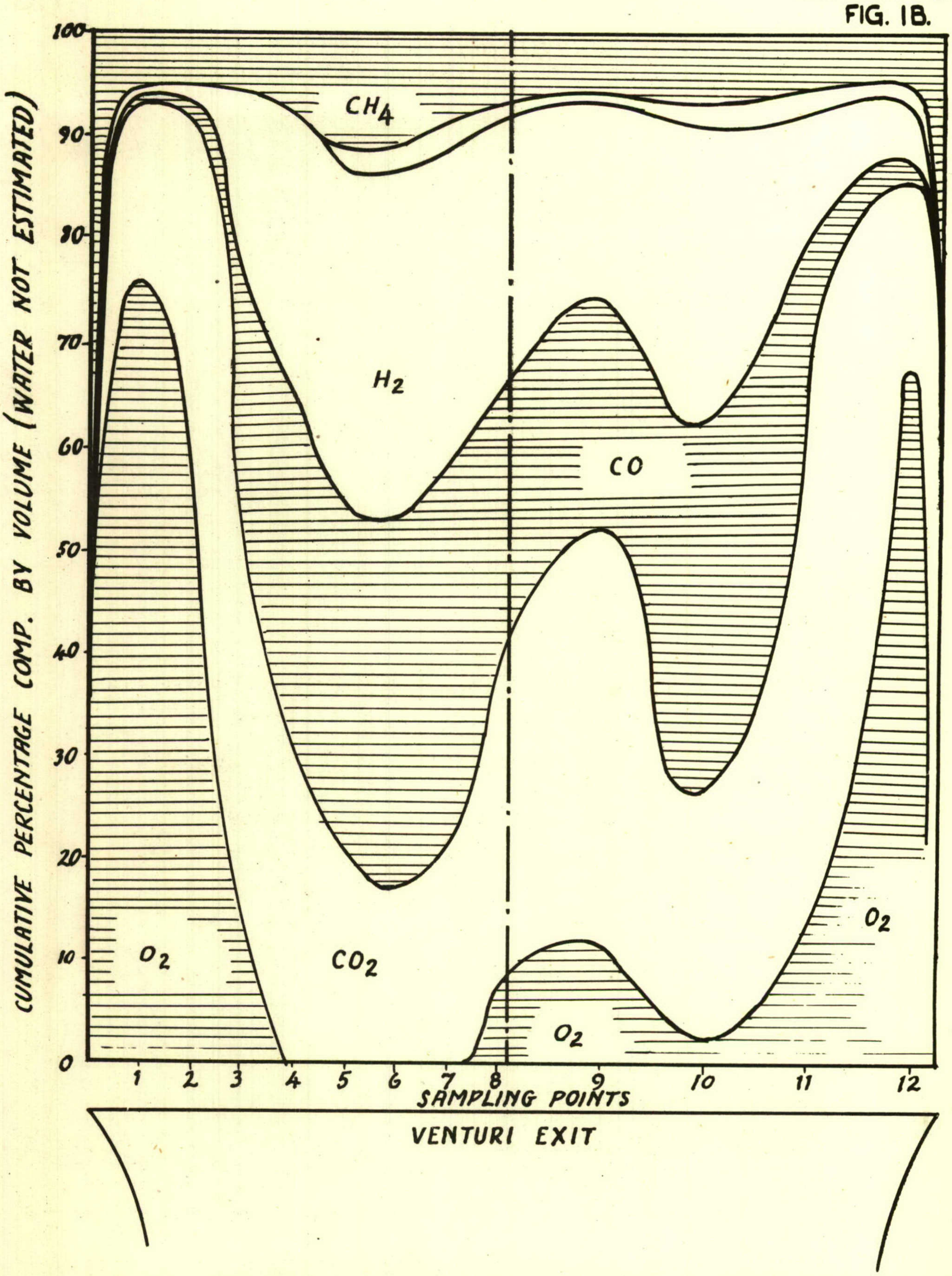


FIG. I. B DISTRIBUTION OF COMBUSTION PRODUCTS FROM VOLUMETRIC ANALYSIS OF EXHAUST GASES OF I TON THRUST COMBUSTION CHAMBER.
INJECTOR SPRAYING RADIALLY OUTWARDS
OXIDANT: LIQUID OXYGEN
FUEL ETHYL ALCOHOL & WATER
ANALYSIS SAMPLES TAKEN 10 MM BEHIND VENTURI EXIT.

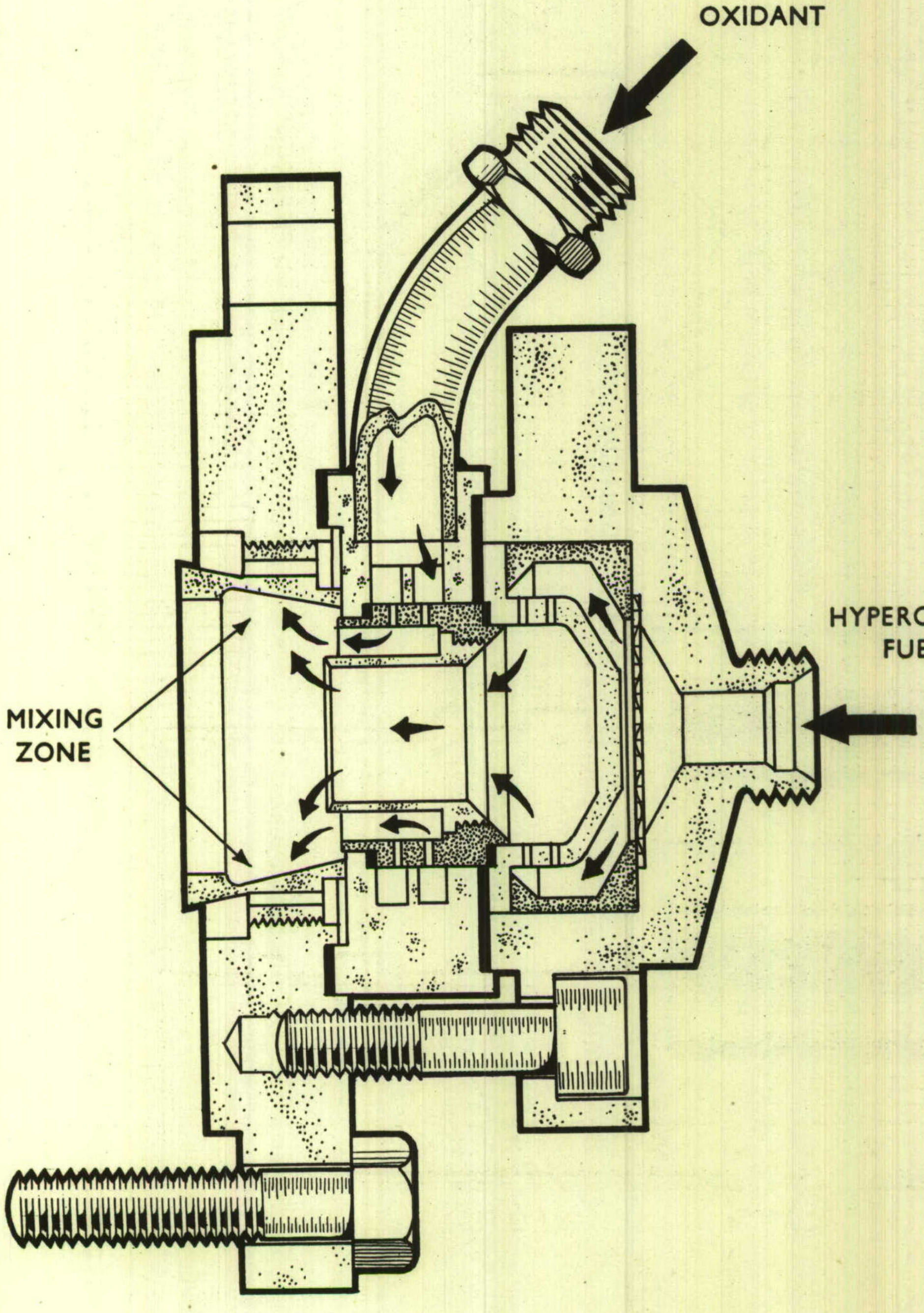


FIG.2. VÖLKENRODE MIXING NOZZLE

FIG.3

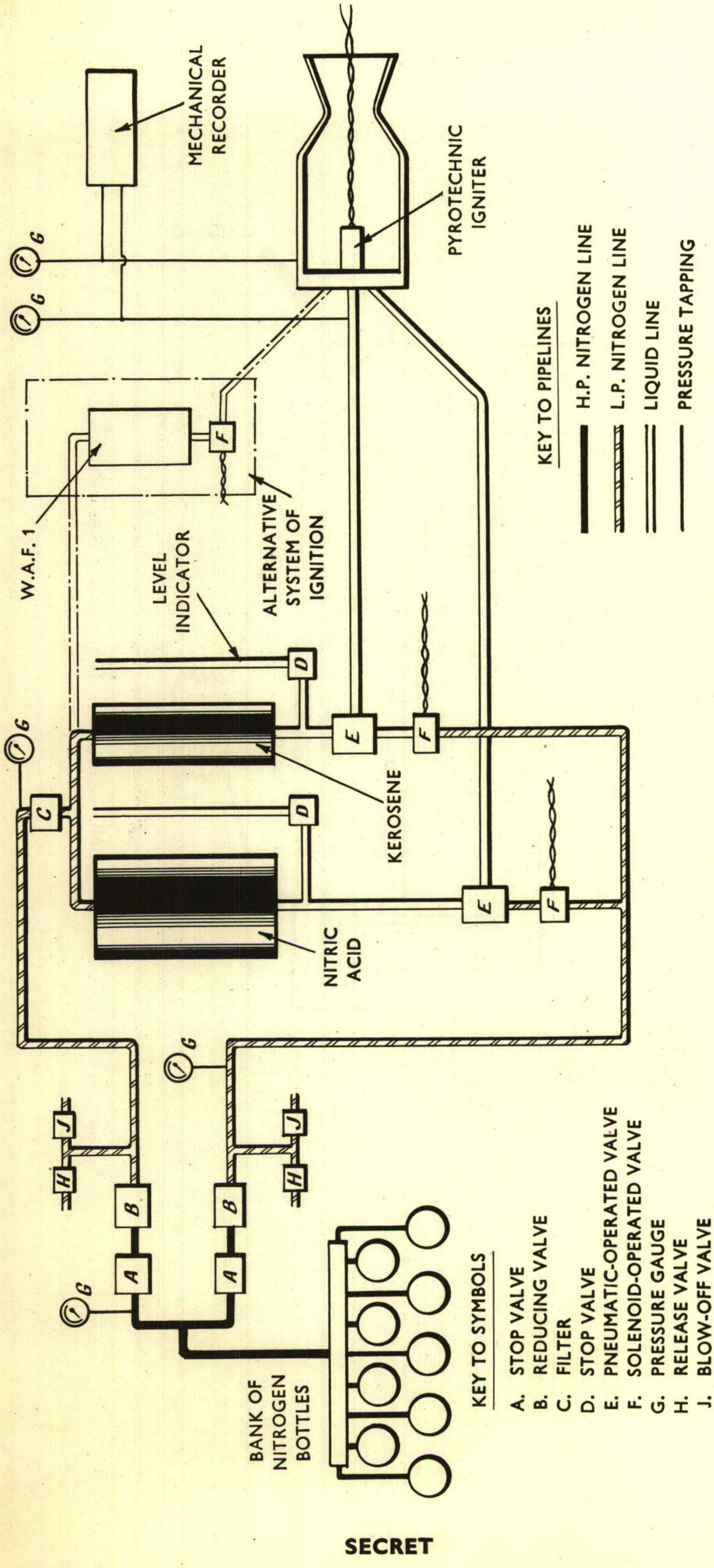
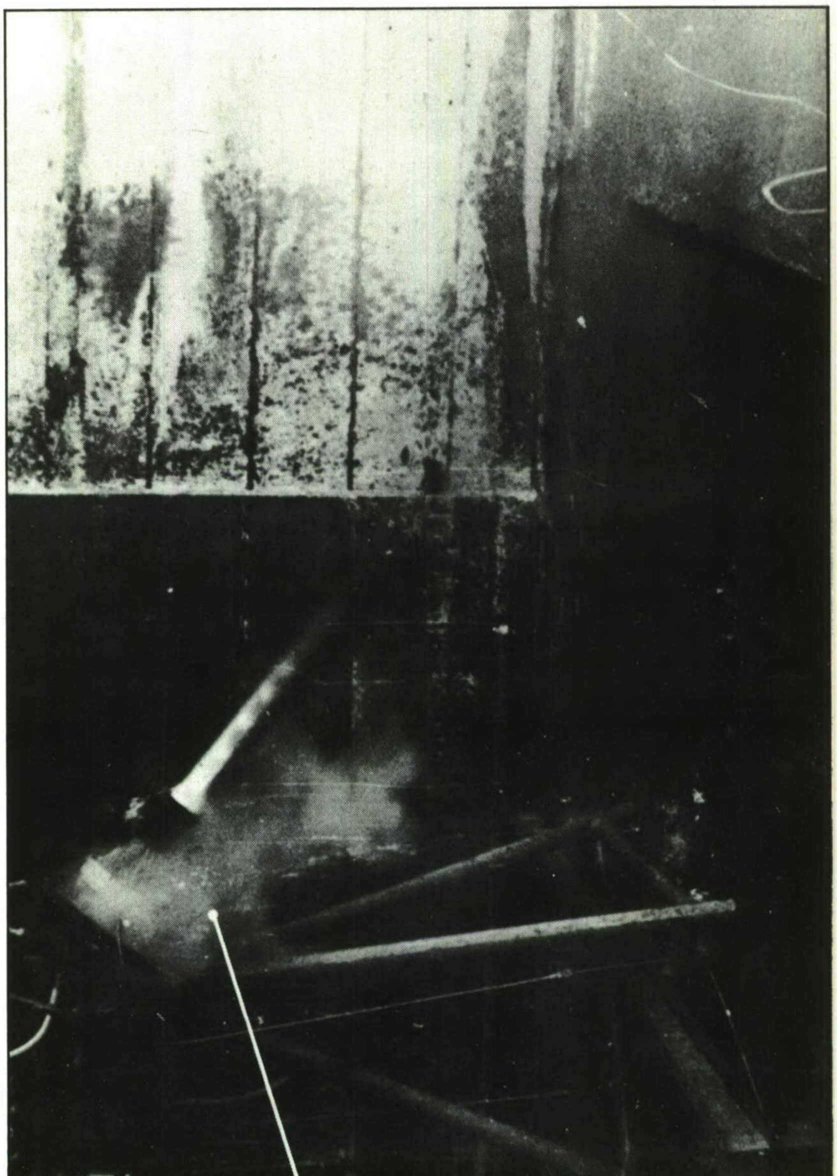


FIG.3. DIAGRAMMATIC LAYOUT OF TEST RIG FOR PRE-MIXING TESTS

FIG.4

COMBUSTION CHAMBER PRESSURE; 130 lb/sq.in. ABS



WHITE VAPOUR IS STEAM FROM EXTERNAL WATER COOLANT SPRAY

FIG.4. PRE-MIXING INJECTOR HEAD No.2 FIRING TEST

FIG.5a

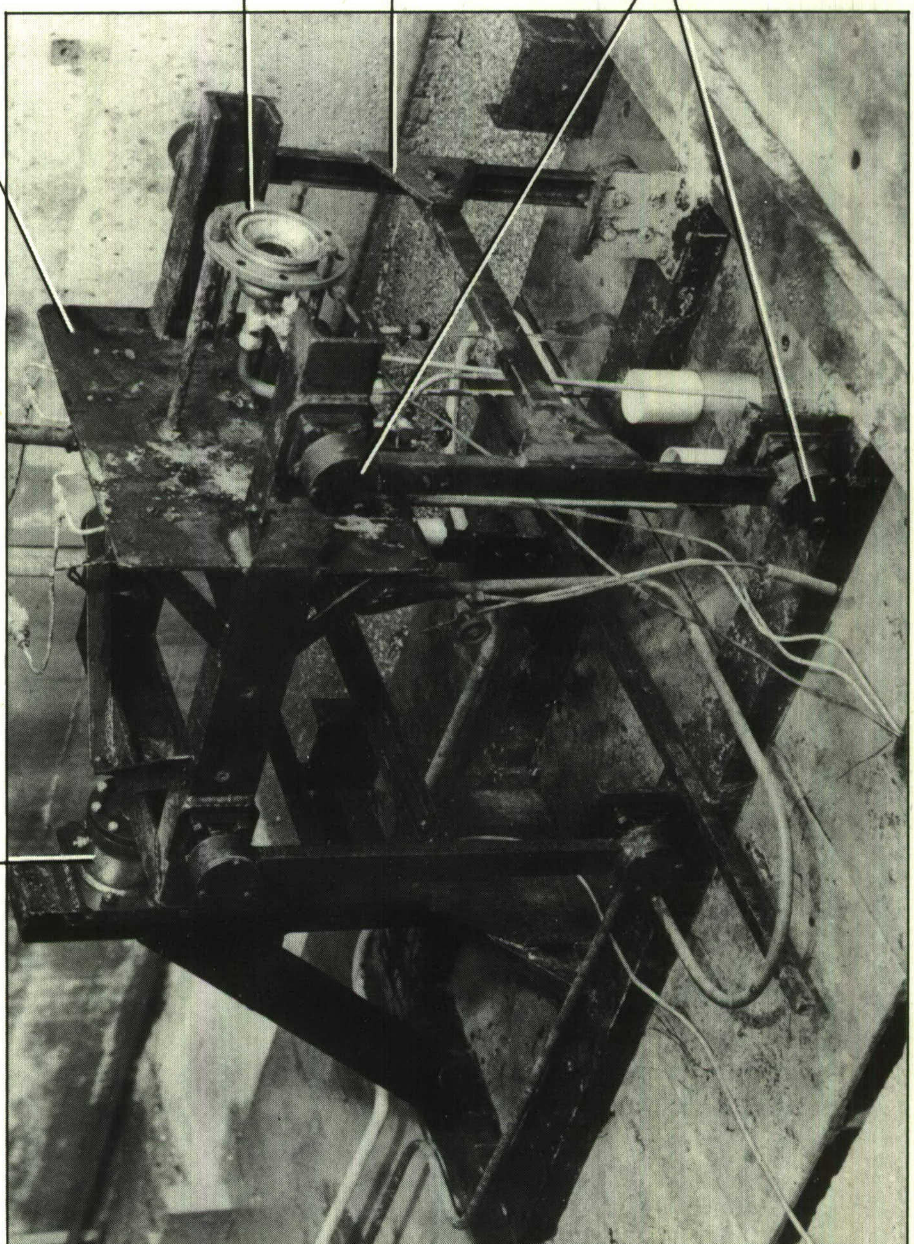


FIG.5a. FRONT VIEW OF TEST RIG

FIG.5b

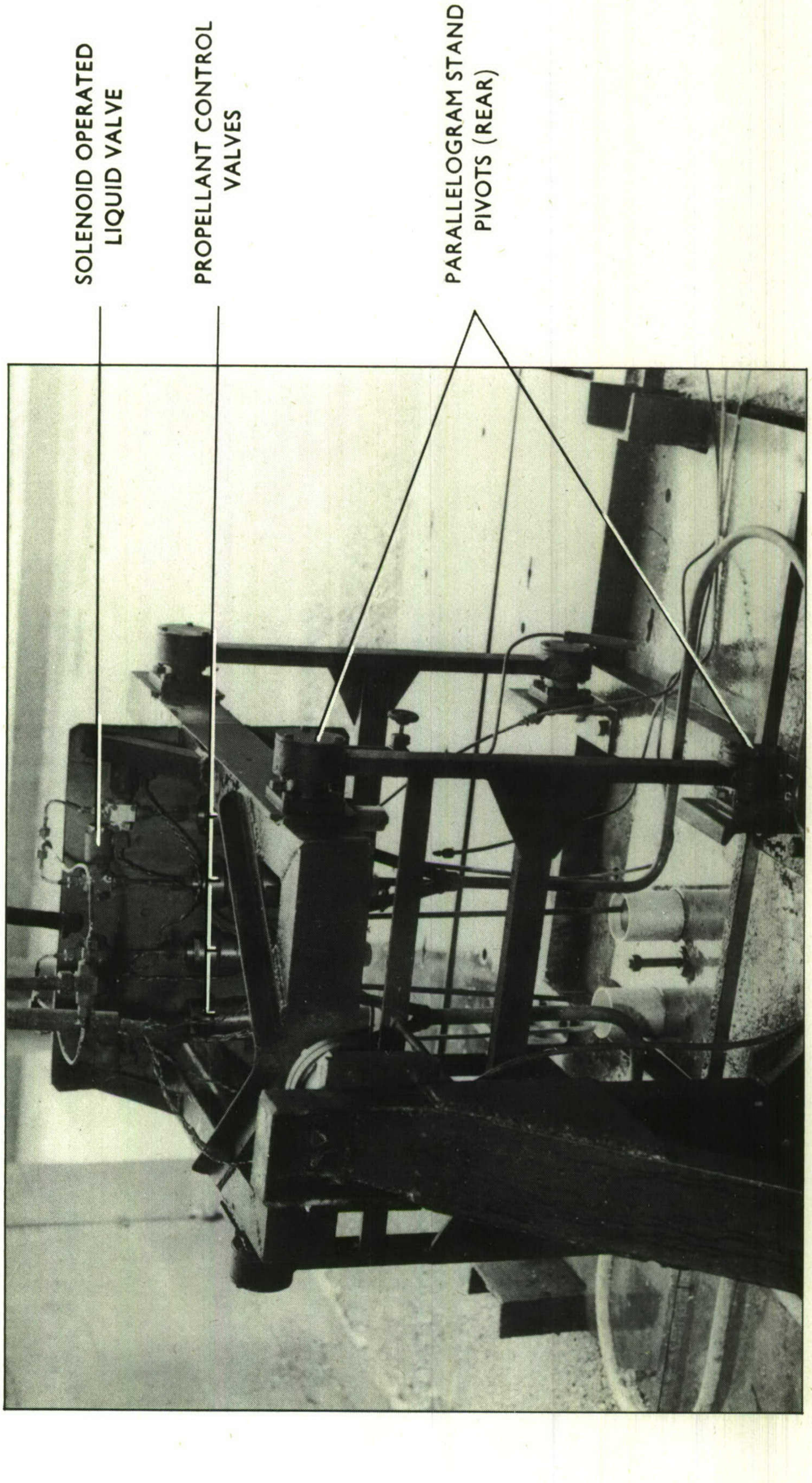


FIG.5b. REAR VIEW OF TEST RIG

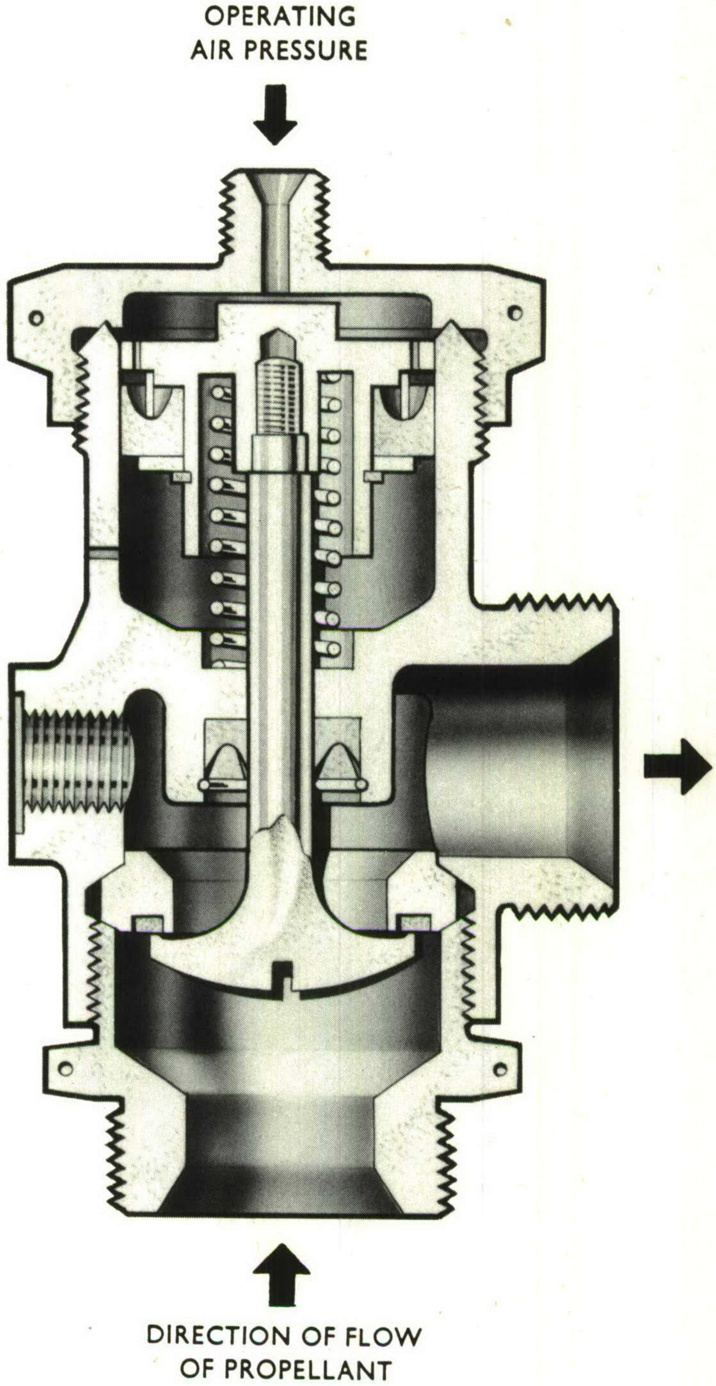


FIG.6. PNEUMATICALLY CONTROLLED PROPELLANT VALVE USED IN TESTS OF INJECTOR HEADS No.1 to 3

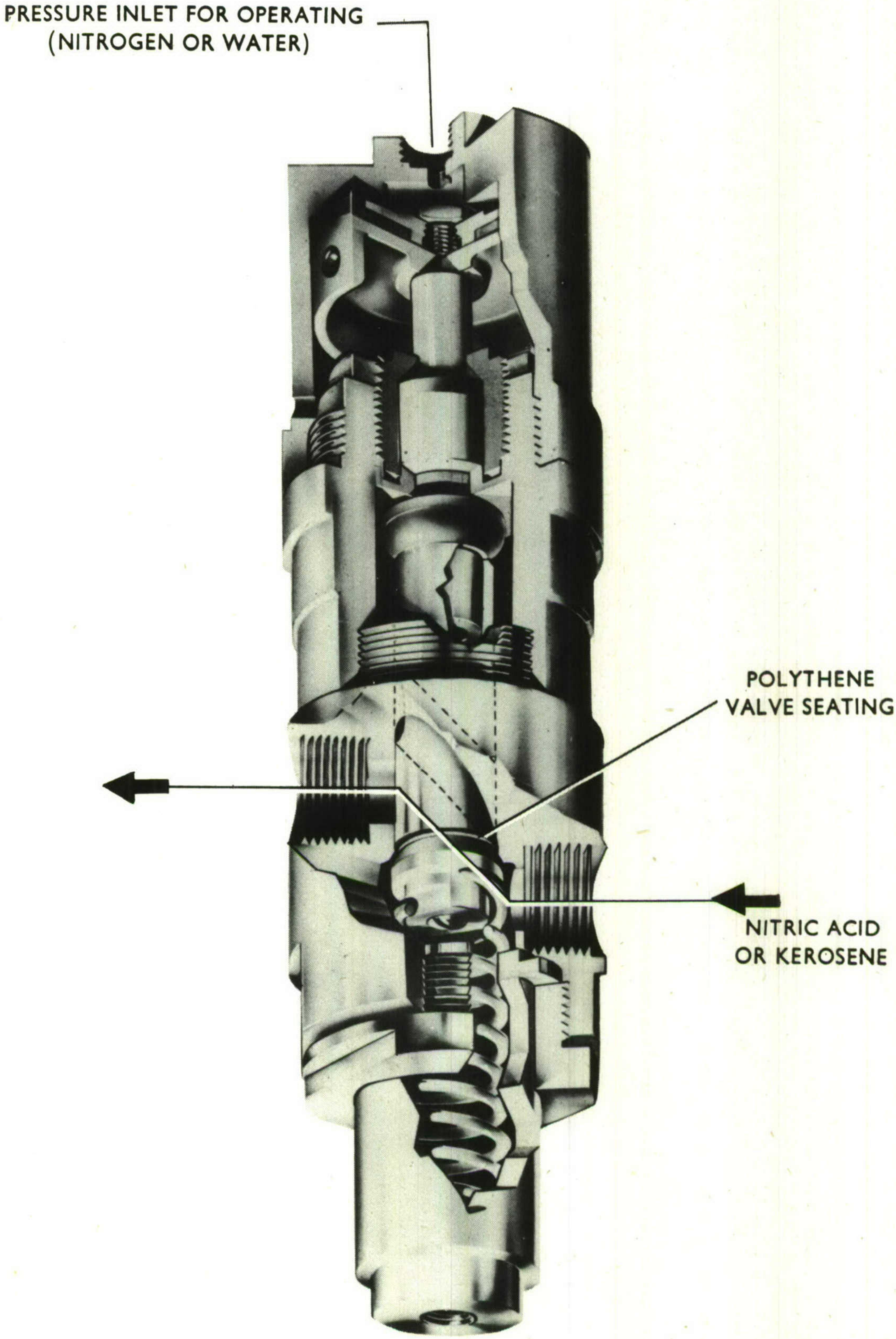


FIG.7. STAINLESS STEEL PNEUMATICALLY OR HYDRAULICALLY OPERATED VALVE USED IN TESTS OF INJECTOR HEAD No.4 & ONWARDS

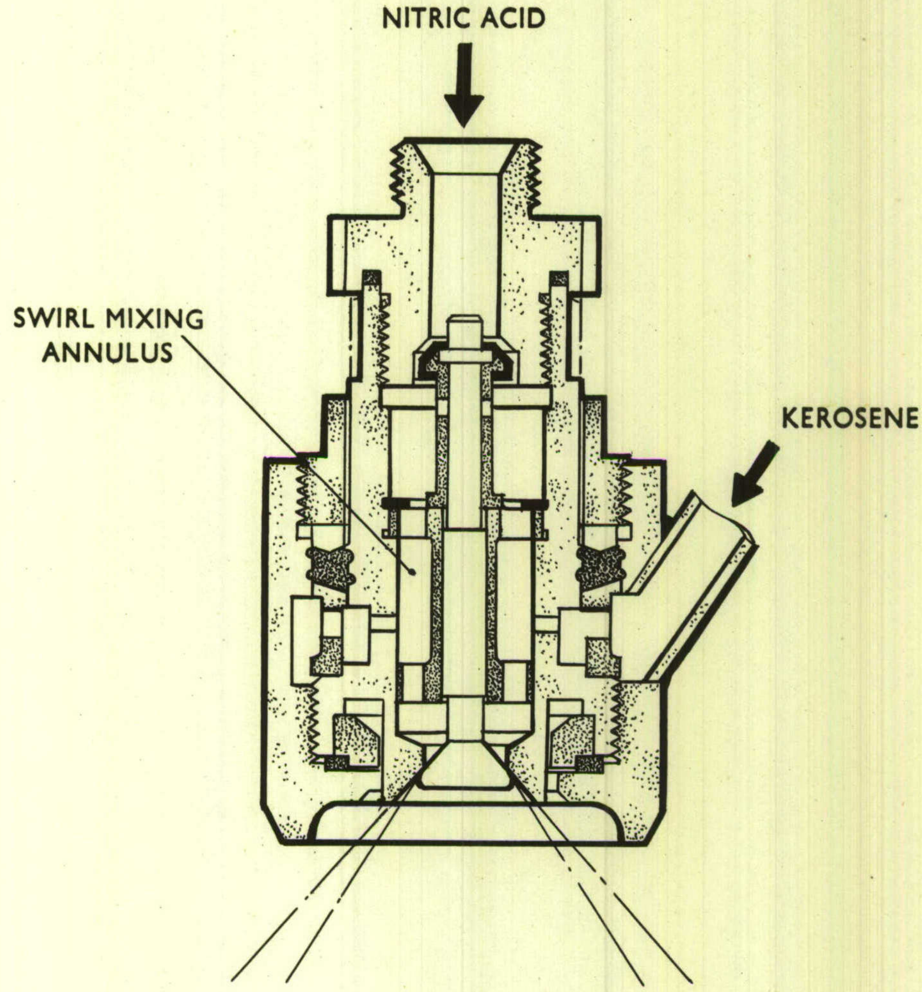


FIG.8. PRE-MIXING INJECTOR HEAD No.1

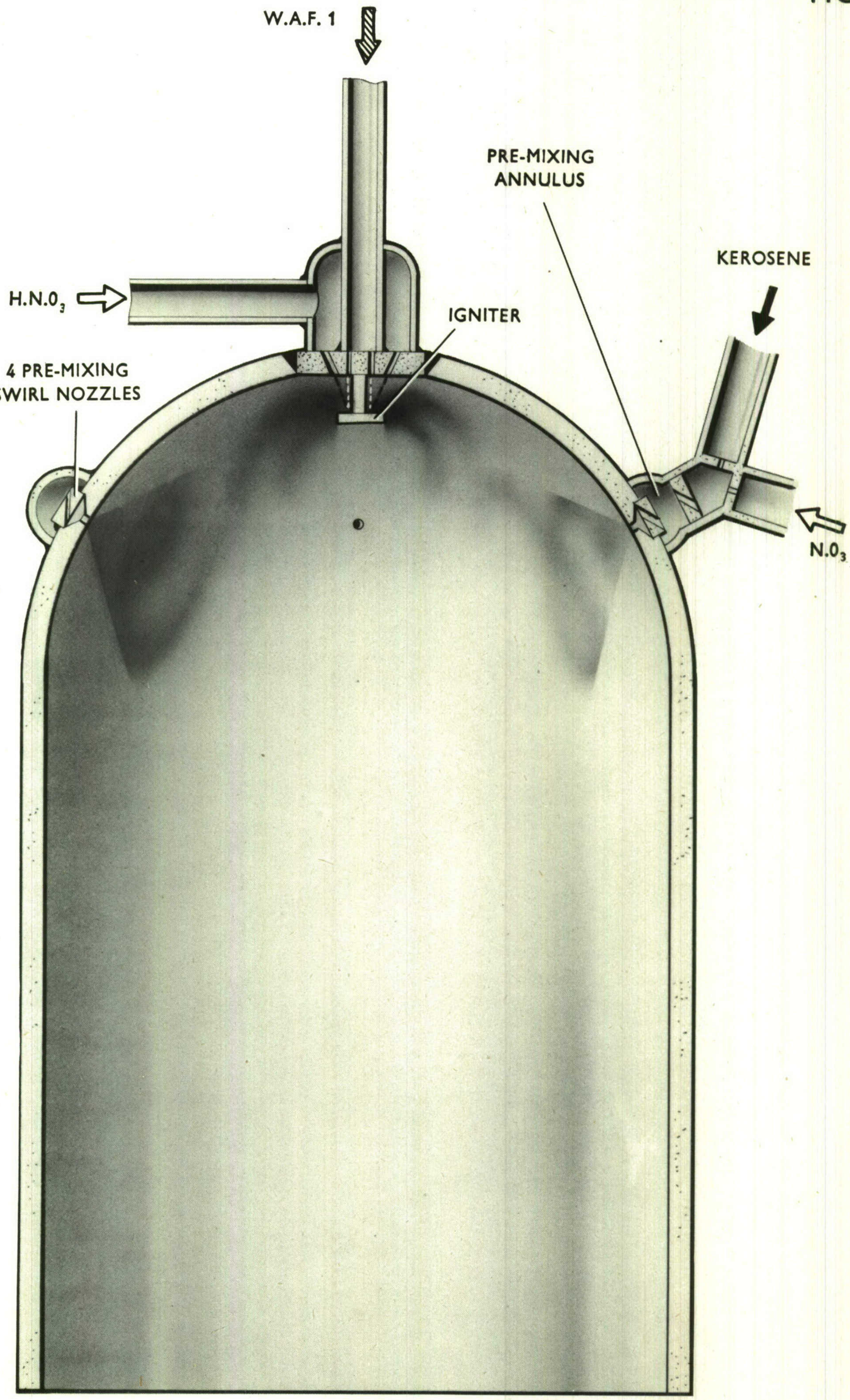


FIG.9. PRE-MIXING INJECTOR HEAD No.2

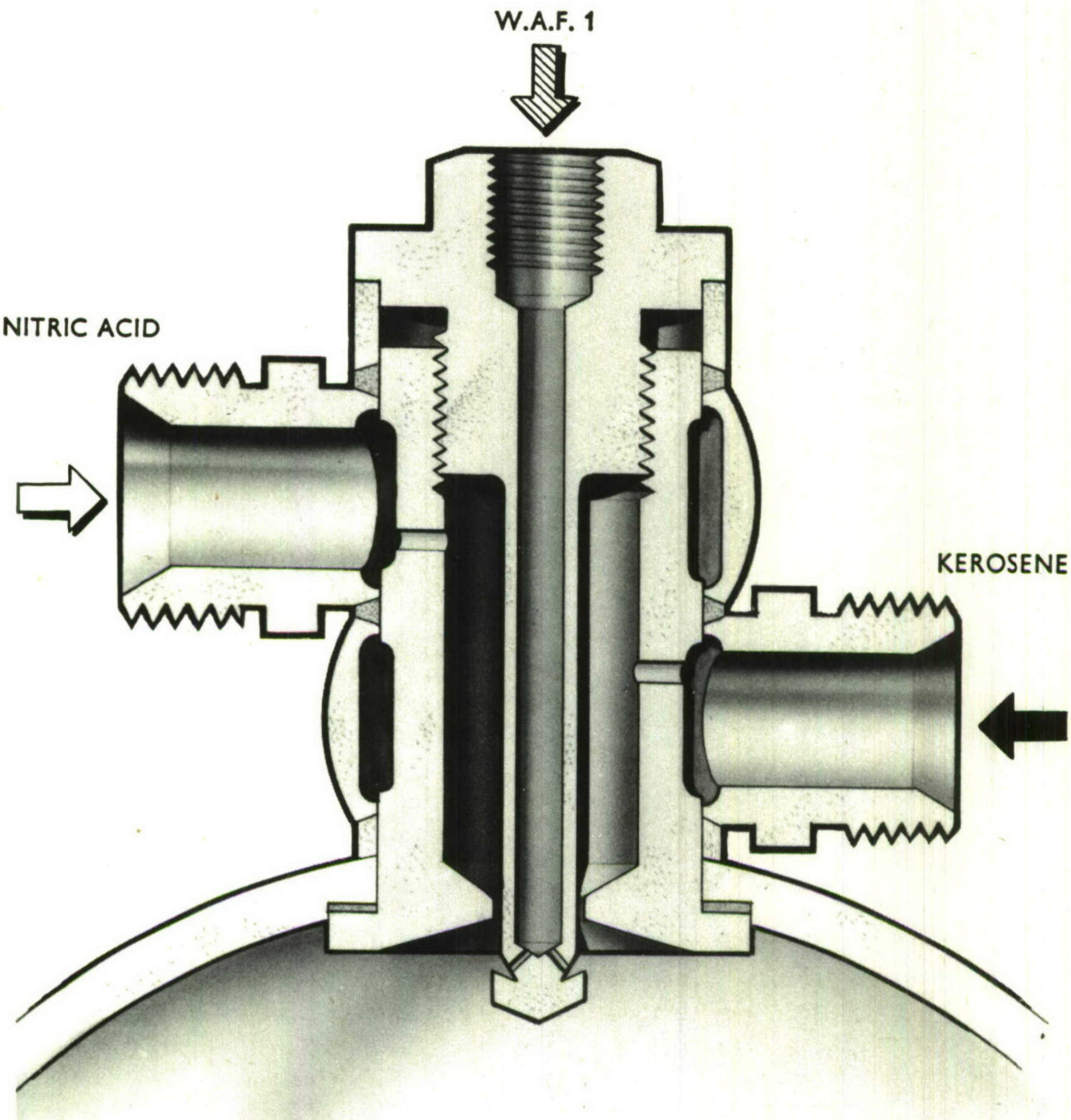


FIG.10. PRE-MIXING INJECTOR HEAD No.3

FIG. 11

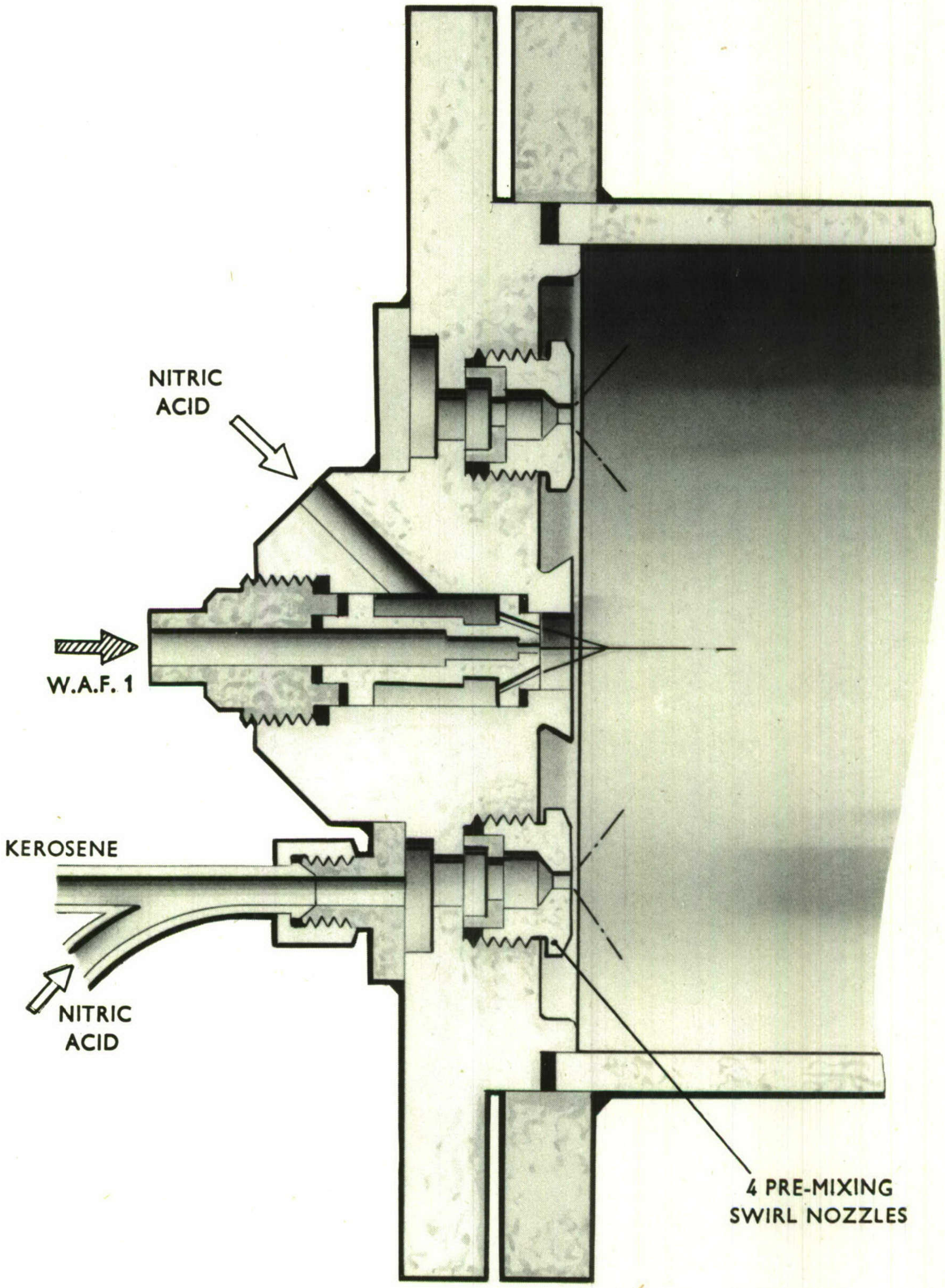


FIG.11. PRE-MIXING INJECTOR HEAD No.4

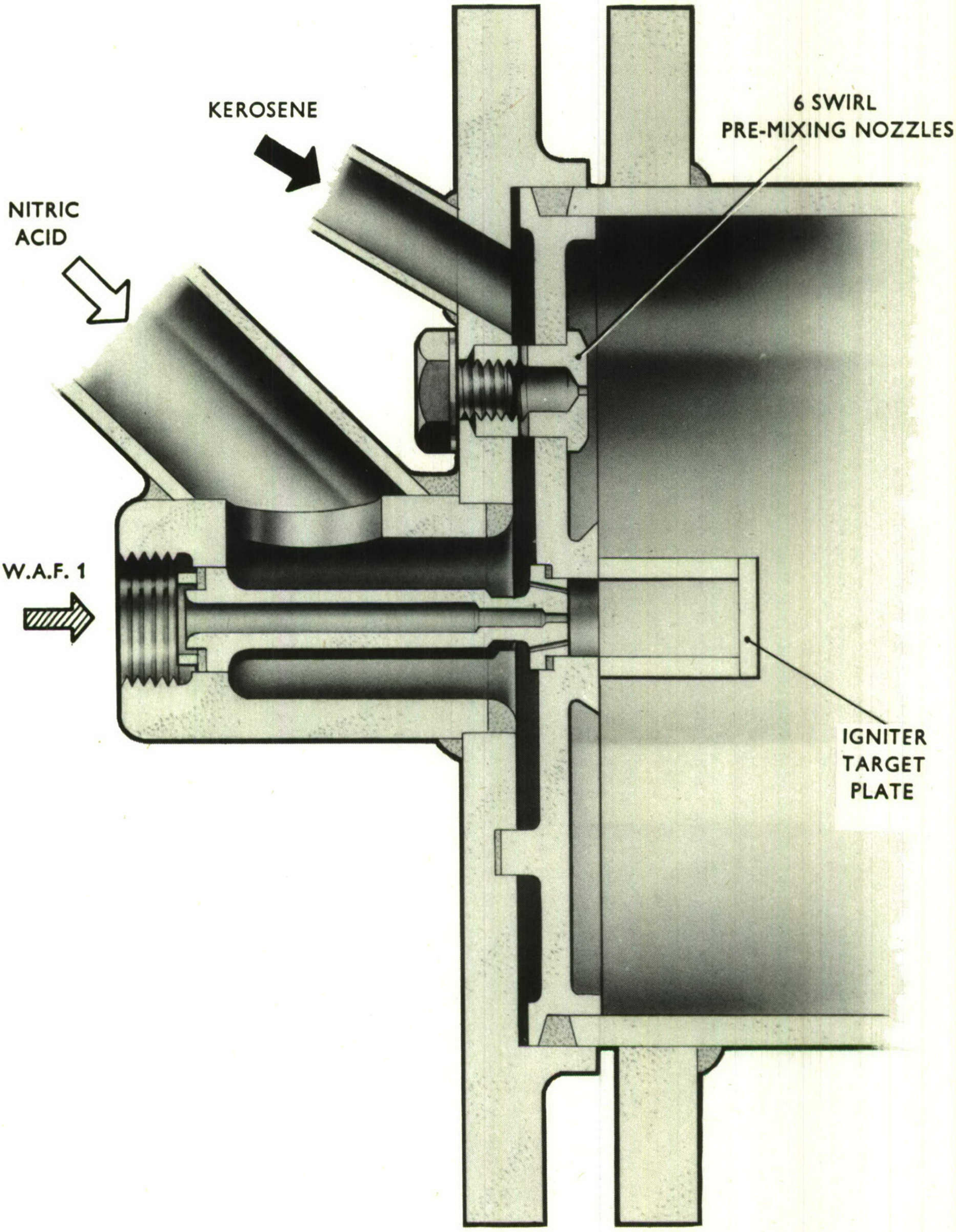


FIG.12. PRE-MIXING INJECTOR HEAD No.5

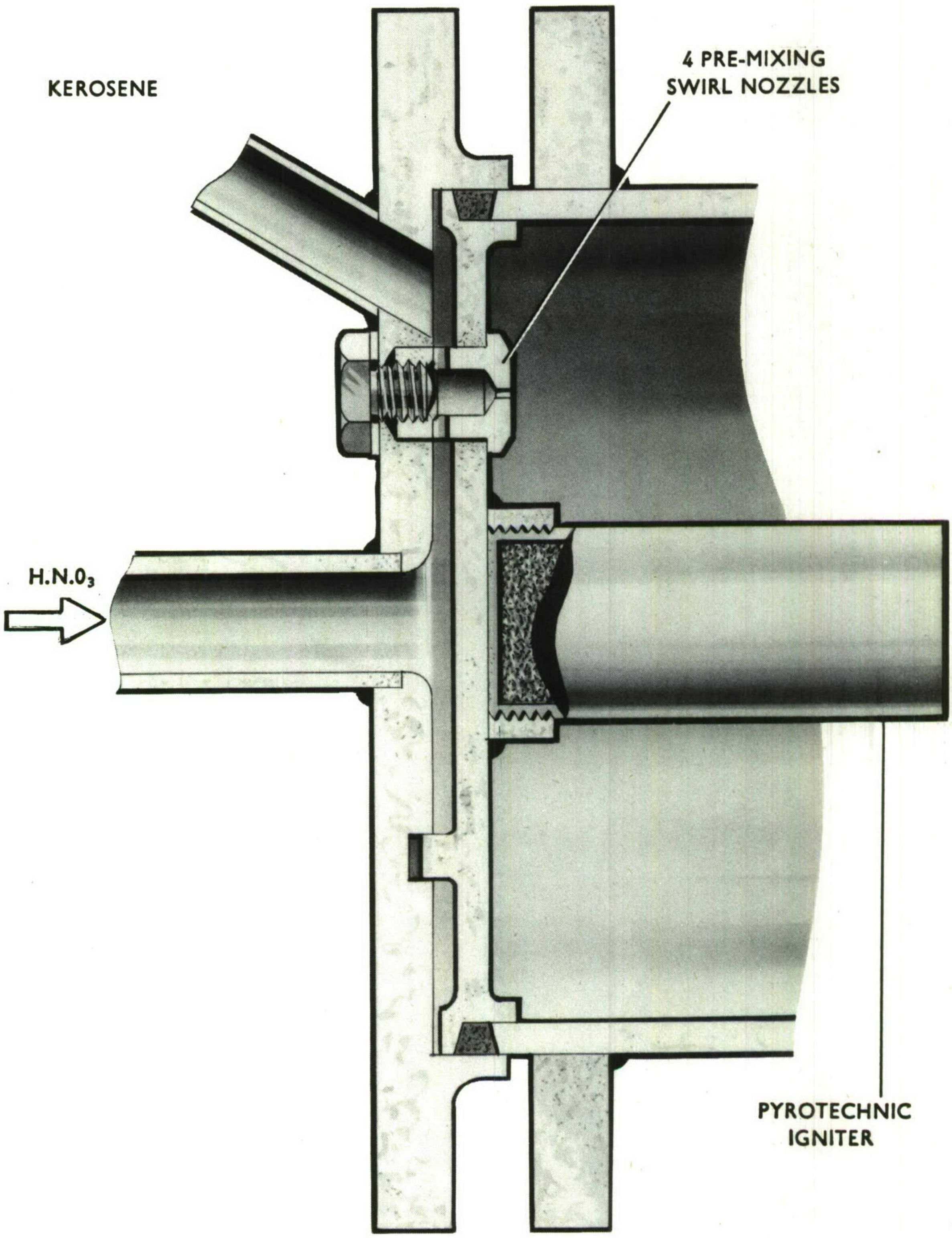


FIG.13. PRE-MIXING INJECTOR HEAD No.6

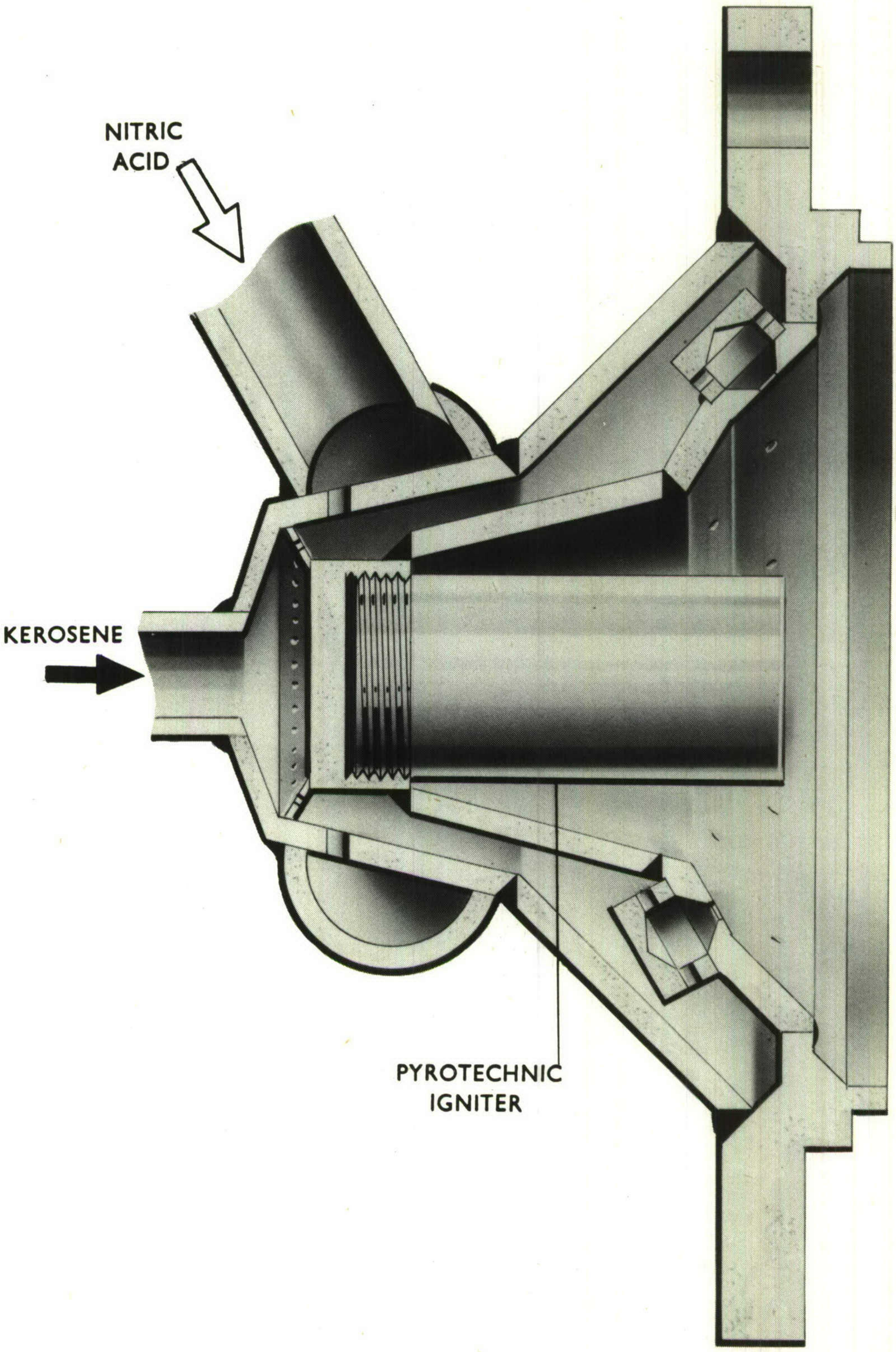


FIG.14. 2000 lb THRUST PRE-MIXING INJECTOR HEAD No.7

No.8(a) HAS 30 SWIRL INJECTORS

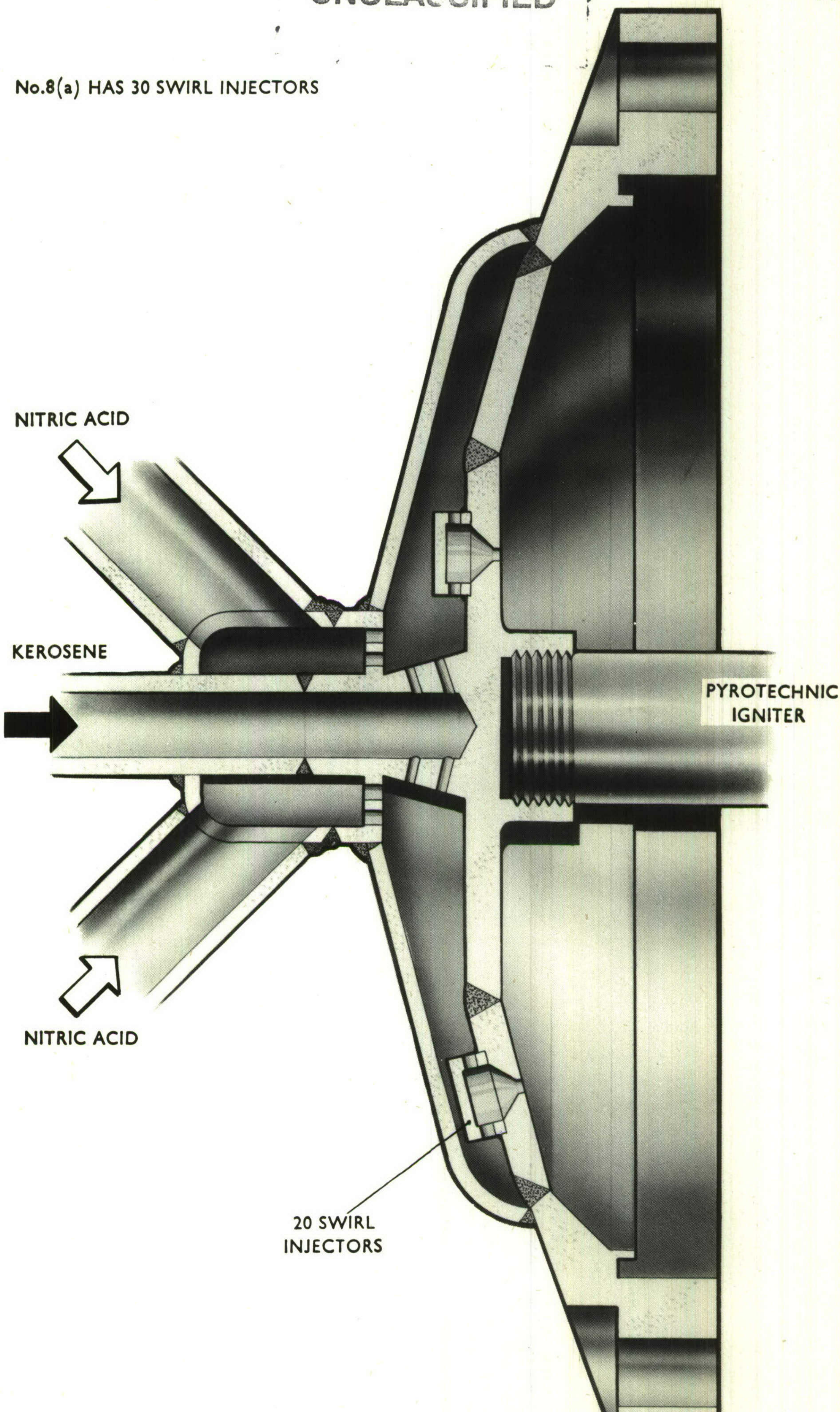


FIG.15. 2000 lb THRUST PRE-MIXING INJECTOR HEAD No.8

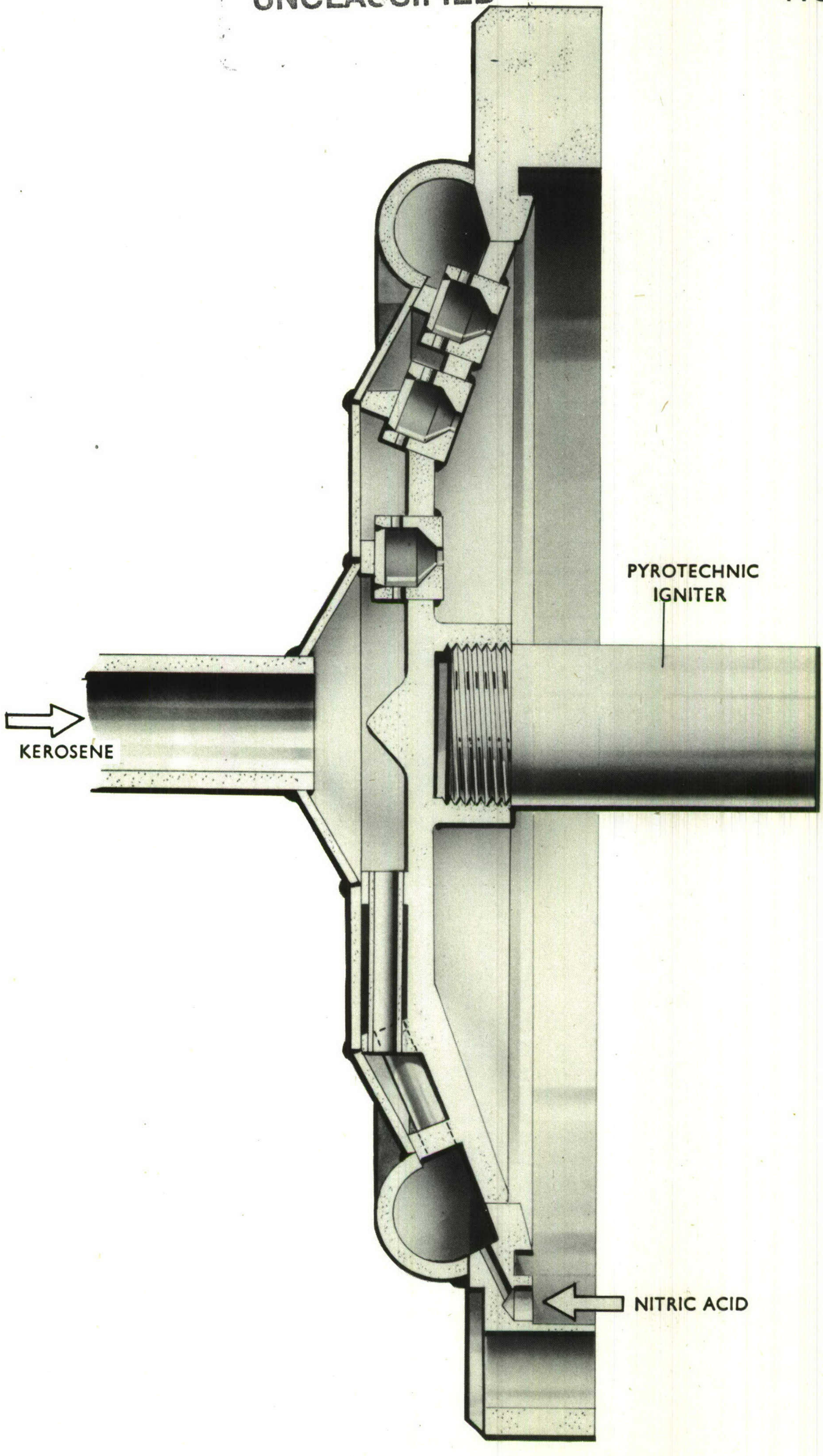


FIG.16. 2000 lb THRUST PRE-MIXING INJECTOR HEAD No.9

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UNCLASSIFIED